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High-resolution measurement of absolute α-decay widths in ^{16}O

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By using a large-acceptance position-sensitive silicon detector array in coincidence with the high-resolution Munich Q3D spectrograph, unambiguous measurements have been made of the absolute α-particle decay widths from excited states in ^{16}O* in the energy range 13.85 to 15.87 MeV. Carbon targets have been bombarded with 42-MeV ^{6}Li beams to induce $^{12}_{6}$C($^{6}_{3}$Li, d)$^{16}_{8}$O* reactions. The deuteron ejectiles were measured in the Q3D and the results gated by ^{4}He + ^{12}C breakup products detected in the silicon array, the efficiency of which was modeled using Monte Carlo simulations. By comparing total population and breakup-gated spectra, the following absolute α-decay widths have been measured with high resolution: $\Gamma_{\alpha 0}/\Gamma_{\rm tot} = 0.87 \pm 0.11$ (13.980 MeV), 1.04 ± 0.15 (14.302 MeV), 0.92 ± 0.10 (14.399 MeV), 0.59 ± 0.04 (14.815 MeV), 0.88 ± 0.18 (15.785 MeV), and $\Gamma_{\alpha 1}/\Gamma_{\rm tot} = 1.14 \pm 0.08$ (14.660 MeV), 0.46 ± 0.06 (14.815 MeV).

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I. INTRODUCTION

Interest in nuclear cluster and molecular states in light nuclei has highlighted the importance of states around the α and multi-α thresholds [1]. For example, it is the presence of such exotic states that enhances heavy element production in stars. Recently, a state with multi-α structure has been predicted in ^{16}O [2–4] around the 4α threshold ($S_{4\alpha} = 14.437$ MeV), a resonance analogous to the Hoyle state in ^{12}C [5]. The focus of this research has recently centered on the 15.1-MeV $I^\pi = 0^+$ state in ^{16}O [6] as a possible Hoyle-type resonance. In the same excitation energy regime lie rotational members of the known cluster bands [7], in addition to other, shell-model-like states. The experimental challenge in determining the structure of these resonances is in the unambiguous elucidation of such excitations around the multi-α thresholds. In particular, cleanly separating states requires good resolution and, to characterize the states, the simultaneous measurement of their absolute α-decay widths. For example, the 15.1-MeV condensate candidate lies within 100 keV of an $I^\pi = 2^-$ level, making high resolution paramount. Here, results from a newly developed experimental setup at MLL Munich are reported for which the absolute decay widths of states around 15 MeV in ^{16}O have been uniquely measured with high resolution.

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II. EXPERIMENTAL METHOD

The 15-MV tandem Van de Graaff accelerator at the Maier-Leibnitz Laboratory (MLL) of the Technical University and Ludwig-Maximillian University, Munich, was used to provide a 42-MeV ^{6}Li beam. A self-supporting, 100-μg cm^{-2} target of $^{\rm nat}$C, placed at the center of the target chamber of the high-resolution Q3D (one quadrupole, three dipoles) magnetic spectrograph [8], was bombarded in order to study the ^{12}C(^{6}Li, d)^{16}O* reaction ($Q_0 = +5.688$ MeV). The deuteron ejectiles were analyzed by the Q3D, the properties of which focus ions of a given energy to the same place on the focal plane, independent of angle, such that focal-plane position corresponds to excitation energy. The Q3D was set at -21.5° with respect to the beam axis and had an acceptance of $\pm 3^\circ$ and $\pm 2^\circ$ in the horizontal and vertical directions, respectively. The Birmingham silicon array, comprised of four double-sided silicon-strip detectors (each 16 horizontal $\times$ 16 vertical strips) in a 2$\times$2 configuration, was placed on the opposite side of the beam axis. The silicon array had a large angular acceptance, covering the angular range 8.4° to 85.4° ($\leftrightarrow$) and 35.4° to -36.4° ($\updownarrow$) with respect to the beam axis. This enabled the measurement of both energy and angle for the recoil or the associated breakup products. Position, energy, and energy loss of the deuterons at the Q3D focal plane were measured using a proportional counter comprised of a cathode foil divided into 255 vertical strips with single-strip readout and 3.5-mm pitch, covering 89 cm. Upstream, two horizontal wire planes registered energy loss. A plastic scintillator downstream of the vertical-strip plane measured energy. Each incident particle

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produced events in 3–7 vertical strips due to the 40°–50° particle incidence angle at the focal plane. (This detector is described in detail in Refs. [9,10].) The position centroid was obtained by fitting a Gaussian to the resulting charge distribution on an event-by-event basis using custom software [11]. The master trigger required a coincidence between the Q3D scintillator and a horizontal wire, i.e., a Q3D singles trigger. For each event, all Si ADC channels were read out with a time window of 5 μs, yielding both Q3D only and Q3D + Si events. Beam currents of 4–5 enA on target were used. In addition, high-statistics, Q3D-only runs were also measured with a beam current of $\geqslant$100 enA. This included collecting data using a 100-μg cm^{-2} U_3O_8 target backed by 10 μg cm^{-2} of ^{nat}C to assess the presence of oxygen reaction products in the data. No states corresponding to ^{20}Ne from ^{16}O contaminants have been observed when using the 100-μg cm^{-2} ^{nat}C target. Two excitation energy regimes were investigated, centered around $E_x = 6.23$ and 14.60 MeV.

During the experiment, the energy resolutions were $\approx$60 keV for the Q3D and $\approx$150 keV for the silicon detectors.

The technique of state-by-state recoil tagging employed here involves observing the total population of a state in the Q3D data. The ratio of this to coincident events from a particular breakup channel detected in the silicon array enables the absolute decay branches to be calculated. The final ingredient in this method is the Si-array efficiency obtained from Monte Carlo simulations of the breakup process.

III. RESULTS

The ^{6}Li projectile preferentially breaks up into $\alpha + d$ ($S_\alpha = 1.47$ MeV) and, consequently, these products are the two dominant transferred ions observed in this experiment. To isolate the α-stripping reactions and remove the background from the deuteron stripping, a series of 2D gates on the scintillator energy ($E_{\rm scint}$), energy loss from each set of horizontal wires ($\Delta E1$ and $\Delta E2$), and position on the focal plane were used. A sample 2D plot with gate is shown in Fig. 1(a). The first excitation range covered 5.20 to 7.95 MeV corresponding to the four lowest excited (bound) states in ^{16}O: 6.049 (0^+), 6.130 (3^-), 6.917 (2^+), and 7.117 (1^-) MeV, all of which decay to the ground state via electromagnetic transitions. As the energies of states are precisely known in this energy region in ^{16}O, the (quadratic) energy calibration of the Q3D focal plane position was straightforward. The ^{16}O excitation energy spectrum is shown in Fig. 1(b). These data demonstrate that contributions from target contaminants are <2%.

Spectra corresponding to all Q3D events and Q3D + Si events were produced from the binary reaction data, the ratio of which is simply the Si-detection efficiency for each state. This efficiency was obtained by using the RESOLUTION8 Monte Carlo simulation code, described in Refs. [12,13]. See later for more details about the simulations. These binary events were used to confirm the beam and detector positions and to establish that the Monte Carlo simulations were accurately modeling the data.

The main aim of the experiment was to investigate the second energy regime around 14.6 MeV, spanning 13.85 to 15.87 MeV, to establish the absolute decay widths of states in this region. The relevant threshold energies in ^{16}O are $S_\alpha = 7.162$ MeV, $S_p = 12.127$ MeV, $S_n = 15.664$ MeV, $S_{^8\rm Be} = 14.620$ MeV, and $S_{4\alpha} = 14.437$ MeV. The possibility of competing breakup channels in the 14.6-MeV domain required the implementation of particle identification for the Si-detector events. This was achieved by plotting hits in the silicon detectors on a Catania plot, as outlined below.

Taking into account the kinematics of the breakup, the detector geometry was chosen such that the data were dominated by single-hit events. Each Si-detector hit was incremented into

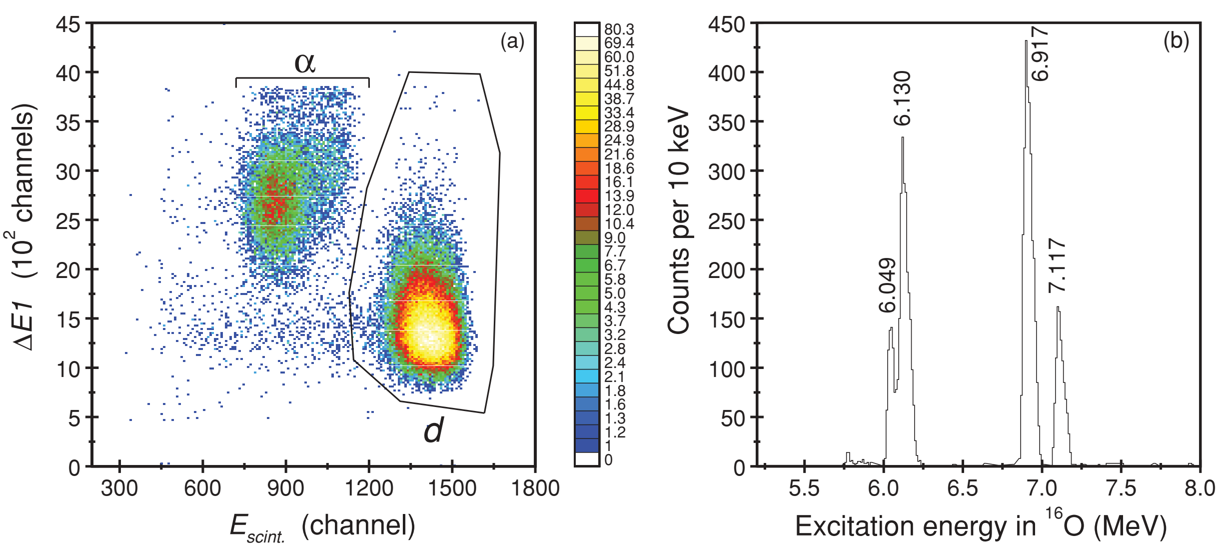

FIG. 1. (Color online) Focal-plane spectra for the Q3D setting at $E_x = 6.23$ MeV. (a) Energy in the scintillator versus energy loss. The events corresponding to deuterons (d) and α particles are labeled. The gate used to select ^{16}O recoils is shown (closed solid black line). The intensity scale is shown to the right. (b) Q3D focal-plane energy spectrum. The peaks in ^{16}O are labeled and correspond to the four lowest excited states. A weak contaminant can be seen at $\approx$5.8 MeV.

several 2D histograms corresponding to the two-body breakup channels

$$^{16}\mathrm{O}^* \to \alpha + ^{12}\mathrm{C}, \quad ^{16}\mathrm{O}^* \to p + ^{15}\mathrm{N}, \quad ^{16}\mathrm{O}^* \to n + ^{15}\mathrm{O}.$$

(No evidence for ^{8}Be from reconstructing double-Si hits was observed. Also, the highest-energy state with a known γ-ray branch lies at 13.09 MeV [7], well below the current region of interest.) For each of the above channels, the single hits were assumed to be the heavier breakup particle. From the angle and energy deposited in the Si detector, the Si events were corrected for energy loss in the target (based on the above assumption regarding the mass), yielding $E_{1\mathrm{corr}}$. Subsequently, the Cartesian components of the momentum $p_1(\mathrm{tot})$ were calculated:

$$\begin{aligned} p_1(\mathrm{tot}) &= \sqrt{2E_{1\mathrm{corr}} m_1}, \\ p_{1x} &= p_1(\mathrm{tot})\sin(\theta_{1x})\cos(\theta_{1y}), \\ p_{1y} &= p_1(\mathrm{tot})\sin(\theta_{1y}), \\ p_{1z} &= p_1(\mathrm{tot})\cos(\theta_{1x})\cos(\theta_{1y}). \end{aligned} \tag{1}$$

The components, i (= x, y, z), of the missing momenta of the second undetected break-up particle, p_{2i}, were calculated using the measured momentum of the deuteron in the Q3D, p_d assuming an angle of -21.5° and the beam momentum p_b. The resulting total momentum of the missing particle, $p_2(\mathrm{tot})$, is found by:

$$\begin{aligned} p_{2i} &= p_{bi} - p_{1i} - p_{di}, \\ p_2(\mathrm{tot})^2 &= \sum_{i=x,y,z} (p_{2i})^2. \end{aligned} \tag{2}$$

Thus, the three-body Q value for the breakup reaction is given by

$$Q_3 = E_d + E_{1\mathrm{corr}} + \frac{p_2(\mathrm{tot})^2}{2m_2} - E_b, \tag{3}$$

where E_d is the kinetic energy of the deuteron calculated from two-body kinematics, knowing the ^{16}O excitation energy. The beam energy at the center of the target is E_b. Rearranging Eq. (3) yields

$$E_b - E_d - E_{1\mathrm{corr}} = \frac{p_2(\mathrm{tot})^2}{2}\frac{1}{m_2} - Q_3. \tag{4}$$

Plotting $p_2(\mathrm{tot})^2/2$ (x) against the left-hand side of Eq. (4), (y) yields a straight line with intercept $-Q_3$ and gradient $1/m_2$, a Catania plot. The slopes of the lines and the intercepts provide mass (particle) identification and excitation energy in the breakup fragment, respectively. Figure 2 shows the Catania plot with the assumption that the detected breakup fragment is ^{12}C, i.e., $m_1 = 12$.

After a detailed study of all possible breakup paths, only the $^{16}\mathrm{O}^* \to \alpha + ^{12}\mathrm{C}$ route has been observed. Consequently, the levels observed in this energy region decay via two distinct states: $\alpha + ^{12}\mathrm{C(g.s.)}$ and $\alpha + ^{12}\mathrm{C}^*(2_1^+)$ with excitation energies in ^{12}C of 0 and 4.439 MeV, respectively. The gates shown in Fig. 2 were used to separate the two final states in ^{12}C and the resulting Q3D spectra are plotted in Fig. 3.

Monte Carlo simulations [12,13] have been performed to obtain the silicon-detector efficiencies for each breakup channel. Isotropic breakup distributions in the center-of-mass frame and energy loss and energy and angular straggling in the target are incorporated. Events were selected in which deuterons fell within the angular acceptance of the Q3D

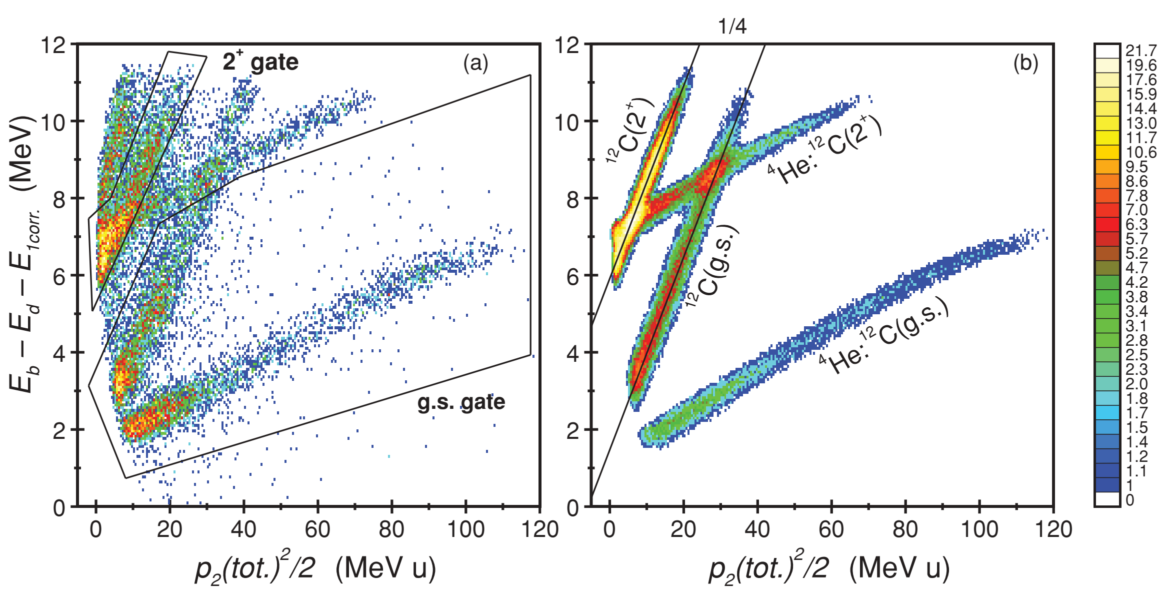

FIG. 2. (Color online) Particle identification (Catania) plots constructed assuming the fragment registered in the silicon array is a ^{12}C nucleus. Four lines [labeled in (b)] are clearly visible. (a) Experimental data: The gates used to select the ^{12}C ground state and 2^+ states are shown (closed solid lines). (b) The corresponding plot from the Monte Carlo simulations. Each line is labeled first by the particle detected in the Si array followed by the state populated in the ^{12}C fragment. The gradient (1/4) of the ^{12}C(g.s.) and $^{12}\mathrm{C}(2_1^+)$ lines is shown above the top axis, demonstrating that both distributions originate from mass =4 fragments (i.e., ^{4}He). The intensity scale is shown on the right.

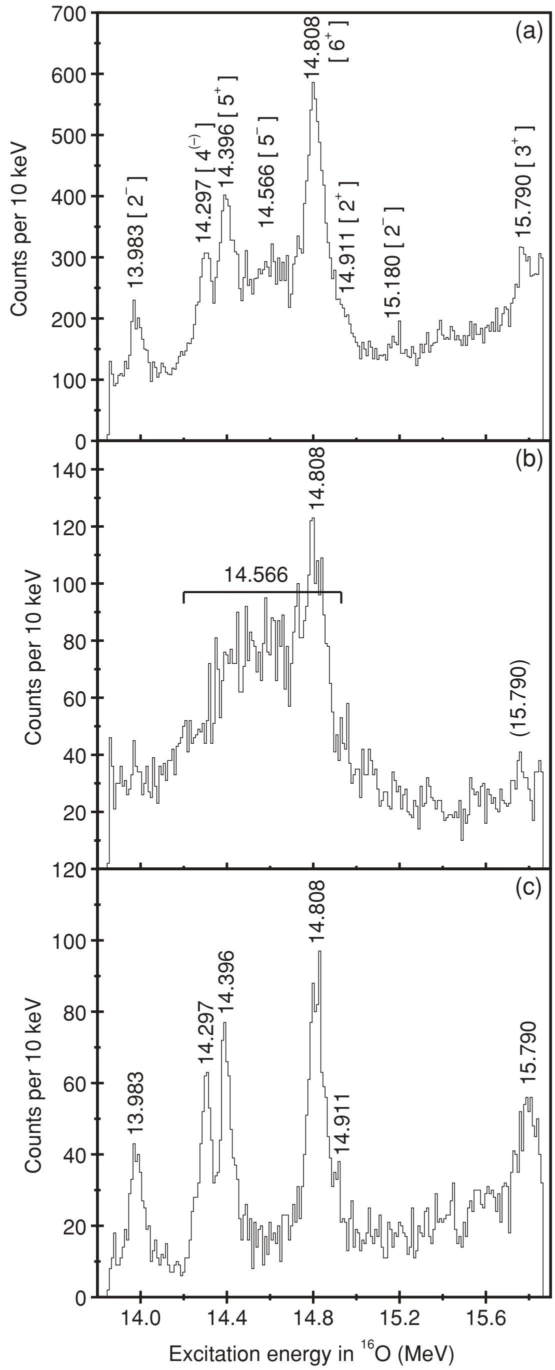

FIG. 3. Focal-plane deuteron spectra for the Q3D setting centered at $E_x = 14.60$ MeV. (a) All Q3D events gated by deuterons in the $E - \Delta E$ plots [see, for example Fig. 1(a)]. States in ^{16}O* are labeled with energy (this paper) and spins and parities [7]. (b) Q3D spectrum as for (a), but additionally using the g.s. gate shown in Fig. 2(a) to select states in ^{16}O decaying to the ^{12}C ground state. (c) Q3D spectrum as for (a), but additionally using the 2^+ gate shown in Fig. 2(a) to select states in ^{16}O decaying to the ^{12}C 2_1^+ state at 4.439 MeV. Note the different vertical scales and background levels. These data represent 58 hours of beam on target.

over a 2-MeV excitation energy range. For bound excited states in the breakup particles (and in the binary recoil for the 6.23-MeV setting), γ-recoil broadening has also been modeled. To minimize uncertainties in the efficiency, 6×10^5 Q3D events have been used, comprised of 3×10^5 events for each of the two final states in ^{12}C. Once incremented into energy ordered arrays, the simulated events were processed using identical sorting code to that used for the experimental data. Detector energy thresholds and nonfunctioning strips in the silicon detectors were also the same as for the experimental data. A sample Catania plot using simulated events is shown in Fig. 2(b). The detection efficiencies for single Si hits using the gates shown in Fig. 2(a) are $\epsilon_{\text{g.s.}} = 40\%$ for the ^{12}C ground state and $\epsilon_{2_1^+} = 37\%$ for the 2_1^+ channel. The spectrum in Fig. 3(a) shows all Q3D events, i.e., both with and without Si coincidences.

The absolute α-decay widths were found using

$$\frac{\Gamma_{\alpha 0}}{\Gamma_{\text{tot}}} = \frac{I[^{12}\text{C(g.s.)}]}{I(\text{tot})\,\epsilon_{\text{g.s.}}} \quad \text{and} \quad \frac{\Gamma_{\alpha 1}}{\Gamma_{\text{tot}}} = \frac{I[^{12}\text{C}^*(2_1^+)]}{I(\text{tot})\,\epsilon_{2_1^+}}, \tag{5}$$

where I(tot) is the total state population from the Q3D data, and $I[^{12}\text{C(g.s.)}]$ and $I[^{12}\text{C}^*(2_1^+)]$ are the intensities of the states gated by the ^{12}C ground and 2_1^+ states, respectively (see Fig. 3). The results are shown in Table I. The states are discussed in turn below, headed by the energies from the compilation in Ref. [7] for clarity. The level energies measured here are quoted in Table I.

13.980 MeV. This $I^\pi = 2^-$ state, observed here at 13.983 MeV, has a decay branch to the 4.439-MeV 2_1^+ in ^{12}C of 0.87 ± 0.11, consistent with its unnatural parity. Unnatural parity states can not break up via $^4\text{He}(0^+) + {}^{12}\text{C}(0^+)$ as the angular momentum coupling of the initial ^{16}O and final ^{12}C states must satisfy

$$\underline{I}_{^{16}\text{O}^*} - \underline{l}_\alpha = \underline{I}_\alpha + \underline{I}_{^{12}\text{C}^*}, \tag{6}$$

where l_α is the orbital angular momentum of ^{4}He and $I_\alpha = 0\hbar$. Therefore, unnatural parity states must decay via the $^{12}\text{C}^*(2_1^+)$ or other nonzero spin levels. The result for the 13.983-MeV (2^-) resonance is in agreement with the observations by Bashkin and Carlson [14], who first reported this state and measured its 2^- character. The dominant decay path was shown to take place via $^{12}\text{C}^*(2^+)$ following $^{15}\text{N}(p,\alpha)$ reactions. No strength has been observed to the ^{12}C ground state [7,14]. These results are confirmed by Hagedorn and Marion [15] using the same proton-induced reactions, and were further able to show that $\Gamma_p/\Gamma < 0.02$. The present value is within two standard deviations of $\Gamma_{\alpha 1}/\Gamma_{\text{tot}} = 1$ and represents the first quantitative measurement of the branching ratio.

A close-lying 0^+ state at 14.032 MeV [16] with a relative α-decay width of 100% is not populated here. Similarly, the 4^+ level at 13.869 MeV, which decays predominantly to the ^{12}C ground state with $\Gamma_{\alpha 0}/\Gamma_{\text{tot}} = 0.65 \pm 0.05$ [7], has not been observed.

14.302 MeV. For the $I^\pi = 4^{(-)}$ 14.302-MeV resonance [7], $\Gamma_{\alpha 1}/\Gamma_{\text{tot}} = 1.04 \pm 0.15$ is consistent with a 100% decay branch and represents the first decay-width measurement for this state. The observed branching ratio is in agreement with its, albeit tentative, unnatural parity assignment.

14.399 MeV. The 14.399-MeV $I^\pi = 5^+$ resonance was first observed by Meier-Ewert *et al.* [17], but in this paper, the first decay-width measurement for this state has been made,

$\Gamma_{\alpha 1}/\Gamma_{tot} = 0.92 \pm 0.10$. This is compatible with the firmly assigned unnatural parity and within one standard deviation of 100%.

14.6 MeV. The most strongly populated state in this study is the broad resonance, observed here at 14.566 ± 0.011 MeV, which decays exclusively to the ^{12}C ground state with $\Gamma_{\alpha 0}/\Gamma_{tot} = 1.14 \pm 0.08$ as measured in the current work. In the compiled data [7], there are two juxtaposed states close to this energy at 14.620 ± 0.020 MeV ($I^\pi = 4^{(+)}$) and 14.660 ± 0.020 MeV ($I^\pi = 5^-$) with total widths of $\Gamma = 490 \pm 15$ and 670 ± 15 keV, respectively. Previous studies have observed relative α-decay widths to the ^{12}C ground state of 0.8 ± 0.1 [7] for the $4^{(+)}$ state and 1.02 ± 0.14 [18], 0.94 ± 0.09 [19], 1.03 ± 0.10 [20], 0.94 ± 0.10 [21], and 0.75 ± 0.15 [22] for the 5^- state.

The majority of studies of $\alpha + {}^{12}$C resonances have observed the 5^- state (see, for example, Refs. [17,19,20,23]), all of which employ the same (^{6}Li, d) reaction and with clear angular distribution measurements [19]. However, three α scattering experiments [6,16,24], all making use of a phase-shift analysis, have found that the best fits to the data require inclusion of a broad, even-spin state, just below the $I^\pi = 5^-$ level. Ames [21], although studying excitation energies above 15 MeV, includes both states when fitting spectra to account for the tails entering the >15-MeV region.

Given the weight of evidence that the $I^\pi = 5^-$ state is the one populated in the α-transfer reactions under similar conditions, it is assumed that the 5^- is populated here. (Note also that a selective measurement showing an angular distribution corresponding to 4^+ has yet to be reported.) With these considerations in mind, the current measurement of $\Gamma_{\alpha 0}/\Gamma_{tot} = 1.14 \pm 0.08$ is in excellent agreement with the compiled average value of 0.94 [7]. Considering only (^{6}Li, d) reactions, the average values are $\Gamma_{\alpha 0}/\Gamma_{tot} 1.03 \pm 0.1$ and $\Gamma_{tot} = 500 \pm 50$ keV at a centroid energy of 14.66 ± 0.02 MeV [7].

14.815 MeV. The $I^\pi = 6^+$ state measured here at 14.808 MeV is strongly populated and decays to both the ground and 2_1^+ states in ^{12}C. The relative α-decay widths in this paper are found to be $\Gamma_{\alpha 0}/\Gamma_{tot} = 0.46 \pm 0.06$ and $\Gamma_{\alpha 1}/\Gamma_{tot} = 0.59 \pm 0.04$. The resulting total decay width of 1.05 ± 0.07 is consistent with earlier measurements reporting approximately equal decay widths to the ground and 2^+ states [19], implying $\Gamma_\alpha/\Gamma_{tot} \approx 100\%$. Furthermore, the branch to the ^{12}C ground state has been previously measured as 0.45 ± 0.05, in excellent agreement with the value obtained here.

14.926 MeV. The 14.911-MeV $I^\pi = 2^+$ state is only weakly populated here and lies at the edge of the broad 14.566-MeV level in the Q3D focal-plane spectra of Figs. 3(a) and 3(c). The spectrum showing the ^{12}C, 2_1^+ decay channels [Fig. 3(c)] shows an excess of counts at 14.911 MeV. However, an accurate α-branching ratio could not be obtained. A prior measurement of $\Gamma_{\alpha 1}/\Gamma_{tot} = 0.54 \pm 0.05$ [7] indicates a qualitative agreement with this work. The 14.911-MeV resonance has a known proton-decay branch with $\Gamma_p/\Gamma_{tot} = 0.36 \pm 0.06$, but this has not been observed here.

15.785 MeV. The highest energy state observed in the current work is the 3^+ 15.790-MeV resonance with $\Gamma_{\alpha 1}/\Gamma_{tot} = 0.88 \pm 0.18$ measured for the first time here. The large uncertainty is due to the state lying at the end of the energy region at the Q3D focal plane making fits to the background less reliable. An upper limit on the branch to the ^{12}C ground state of <0.3 has been possible. However, the small excess of counts in this region in Fig. 3(b) is shifted in energy to 15.760 MeV and could be due to fluctuations in the background. Given the unnatural parity of this state, it can only decay to nonzero spin states in ^{12}C. Previously, no decay paths have been measured for the 15.790-MeV level. There is no evidence for the population of the nearby 15.828-MeV $I^\pi = 3^-$ [$\Gamma_{tot} = 700(120)$ keV] state in the current reaction.

Note that, in the Q3D spectrum of Fig. 3(a), there is evidence for a weakly populated level at 15.180 MeV, most likely corresponding to the 15.196-MeV $I^\pi = 2^-$ state. However, there are insufficient counts to obtain information about the decay path. There is no evidence that the current reaction populates the close-lying 15.096-MeV 0^+ state. See discussion below.

IV. DISCUSSION AND SUMMARY

Comparing the results of this work to similar studies in the literature, the population profile of the present investigation stands out. A broader range of states has been populated here

TABLE I. Absolute α-decay widths measured in this paper and comparison with literature (lit.) values.

E_{level}[a] (keV)	I^π[b]	FWHM [a] (keV)	$\Gamma_\alpha/\Gamma_{tot}$[a] ^{12}C($g.s.$)	^{12}C*(2_1^+)	E_{level} (lit.)[b] (keV)	Γ_{tot} (lit.)[b] (keV)	$\Gamma_\alpha/\Gamma_{tot}$ (lit.)[c] ^{12}C(g.s.)	^{12}C*(2_1^+)
13983(2)	2^-	70(6)	<0.09	0.87(11)	13980(2)	20(2)	0	Large
14297(3)	$4^{(-)}$	66(7)	<0.05	1.04(15)	14302(3)	34(12)		
14396(2)	5^+	64(5)	<0.05	0.92(10)	14399(2)	27(5)		
14566(11)	5^-[c]	450(27)	1.14(8)		14660(20)	670(15)	0.94	
14808(3)	6^+	93(6)	0.46(6)	0.59(4)	14815.3(16)	70(8)	0.45(5)	
14911(20)	2^+	103(30)		~0.2	14926(2)	54(5)	0.027(2)	0.54(5)
15790(5)	3^+	136(13)	<0.3[c]	0.88(18)	15785(5)	40(10)		

[a]This paper.
[b]From Ref. [7].
[c]See text for details.

than previously reported for α-transfer reactions, of which the majority are unnatural parity states. In the compilation of Tilley *et al.* [7], a comparison of ^{12}C(^{6}Li, d) and ^{12}C(^{7}Li, t) reactions has been made, which broadly follows the observations of Becchetti *et al.* [25]. The only common states between these previous works and Table I are the 14.660-MeV $I^\pi = 5^-$ and 14.815-MeV $I^\pi = 6^+$ resonances. [*Note.* The α-transfer compilation [7] includes a state at 14.363(15) MeV, which lies close in energy to the 14.399-MeV level; however, the spin and parity are quoted as >5 and *natural*, respectively.] Notably, Becchetti and co-workers [25] used the same reaction and beam energy: ^{6}Li + ^{12}C at 42 MeV, and recorded deuterons in the Brookhaven Q3D, with a comparable resolution of ≈40 keV. The spectra are dominated by natural-parity states from direct α transfers at low scattering angles (5°). However, a 2^- state at 8.872 MeV was observed in addition to cross-section enhancements for some natural parity states that have been explained by the contribution of compound nuclear processes. These contributions have been effectively modeled using statistical Hauser-Feshbach calculations [25] with ^{6}Li fusion followed by deuteron evaporation. The larger scattering angle of $\theta = -21.5°$ used in the present work is more likely to select compound events, confirmed by the observation of both natural and unnatural parity states. Two of the three natural parity states are strongly populated, 14.566 and 14.808 MeV, most plausibly due to the additional direct α-transfer process contribution to the cross sections. The third natural parity state $I^\pi = 2^+$ at 14.911 MeV is weakly populated, but is not a ^{12}C + α resonance and is, therefore, populated at the same level as the unnatural parity states via compound nuclear processes. The 14.911-MeV state appears in p + ^{15}N scattering [7].

The experimental results in Table I show only one natural parity state that decays exclusively to the ground state of ^{12}C, namely, the 14.660-MeV $I^\pi = 5^-$ level with $\Gamma_\alpha/\Gamma_{\rm tot} = 1.14 \pm 0.08$. This strongly supports its interpretation as an extended α-cluster state. Nearby levels with equal or higher total angular momenta decay either to both levels in ^{12}C or predominantly to the 2_1^+ state. This implies that, for comparable sizes (i.e., Coulomb barriers), the angular momentum barrier is such that it is preferable for the α particle to carry less angular momentum by $2\hbar$ [see Eq. (6)]. However, for the $I^\pi = 5^-$ resonance, the larger radius reverses the situation and the angular momentum is carried exclusively by the α particle as orbital motion. The same is true for the other known α-cluster band members, as given in Table. II.

The dominant decay to the ^{12}C(g.s.) coupled with the large widths for states in the $K^\pi = 0^+$ and 0^- α-cluster bands of Table II and the $I(I+1)$ relation is consistent with the states having the same underlying structure. Furthermore, the precise value (a 4% uncertainty) of the decay width now obtained for the $I^\pi = 5^-$ cluster state provides a stringent test for any theory making predictions of such cluster structures in ^{16}O.

One final point to note is that the 15.096-MeV 0_6^+ state [6], proposed as a candidate for an α-condensed state [2–4], has not been significantly populated in the current work. This is most likely due to angular momentum matching conditions not being met at this excitation energy; as noted earlier, the 14.032-MeV $I^\pi = 0^+$ resonance has also not been observed. However, the population of the immediate neighboring states demonstrates that the resolution achieved here would be sufficient to distinguish the 15.1-MeV resonance. A large area Si array at the Q3D target position, in conjunction with either inelastic α scattering on ^{16}O or ^{14}N(α, d)^{16}O reactions, would be an ideal way to study the properties of this resonance and the associated rotational band [3].

To summarize, the ^{12}C(^{6}Li, d)^{16}O* reaction has been performed at a bombarding energy of 42 MeV. The high-resolution Munich-Q3D spectrograph was used to detect the outgoing deuteron ejectiles at excitation energies around 6.23 and 14.60 MeV. A large-acceptance silicon detector array near the target position has been used to register the recoil and recoil breakup products. In the latter case, Catania plots have been used to identify the breakup fragments. Monte Carlo simulations of the detector geometry with isotropic breakup distributions yielded Si-detection efficiencies for one fragment of 40% and 37% for the α + ^{12}C(g.s.) and α + ^{12}C*(2_1^+) breakup channels, respectively. Using this setup, absolute α-decay widths have been measured without ambiguity, many for the first time.

TABLE II. Absolute α-decay widths measured for members of the α-cluster bands in ^{16}O [7].

K^π	$E_{\rm level}$ (keV)	I^π	$\Gamma_{\rm tot}$ (keV)	$\Gamma_\alpha/\Gamma_{\rm tot}$ ^{12}C(g.s.)	$\Gamma_\alpha/\Gamma_{\rm tot}$ ^{12}C*(2^+)	$\Gamma_\gamma/\Gamma_{\rm tot}$ ^{16}O(g.s.)
0^+	6049.4(10)	0^+	Bound			1.00[a]
	6917.1(6)	2^+	Bound			1.00
	10356(3)	4^+	26(3)	0.86(9)		2.38×10^{-6}
	16275(7)	6^+	420(20)	0.982(48)[b]		
	22500(500)	(8^+)[c]				
0^-	9585(11)	1^-	420(20)	∼1		6.67×10^{-8}
	11600(20)	3^-	800(100)	1.00		
	14660(20)	5^-	670(15)	1.002(42)[d]		
	20857(14)	7^-	900(60)	1.16(23)		

[a] $\Gamma_{ce}/\Gamma_{\rm tot}$.
[b] Average from Ref. [18].
[c] From Ref. [22].
[d] Combined weighted average from the average quoted in Ref. [18] and this paper.

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